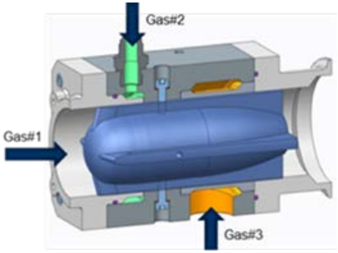
High-Efficiency Cost-Effective Natural Gas Engine



P.I. – Alex Freitag, Director of Engineering, Diesel Systems

Presenter – Steve White

Robert Bosch LLC

2017 DOE VTO Annual Merit Review

June 8th, 2017

Project ID #**FT058**

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Overview

Timeline

- Project awarded = 12/2/2015
- Project start date = 1/1/2016
- Project end date = 9/30/2018
- Percent complete = 45%

Budget

- Total project funding
  - Total project = $3,537,384
  - DOE share = $1,756,225
  - Contractor share = $1,781,159
- Funding received in FY 2016
  - $699,084
- Funding for FY 2017
  - $424,285

Barriers

- Goal
  - Increase engine efficiency through optimized dilution with both EGR and excess air
- Key Enablers
  - Advanced ignition system for robust combustion with high dilution
  - Lean capable exhaust aftertreatment system
  - Improved response fuel system (feedgas composition control)
- Targets
  - Peak Brake Thermal Efficiency > 42%
  - EPA17 On-Highway Emissions

Partners

- Bosch – Project Lead
- University of Michigan
- PNNL

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Overview – Project Scope

Conditions considered valid & not valid for this project:

- In Scope:
  - Use of an existing base engine
  - No changes to existing combustion chamber
  - Utilize existing proven hardware wherever possible
  - Utilize advanced systems where practical via near production ready & technical resources ability to support project
- Out of Scope:
  - Base engine redesign
  - Redesign of combustion chamber (piston, head, # valves/cyl., compression ratio, etc.)
  - Change combustion chamber mixture motion (tumble, swirl, etc.)
  - Compression ratio optimization
  - Intake manifold optimization
  - Etc.

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Relevance/Project Objectives

- Demonstrate a natural gas fueled heavy-duty engine capable of increasing efficiency from current state-of-the-art of ~35%, achieving a near-diesel BTE of approximately 42%.

- Methodology:
  - Engine operation will traverse lean and stoichiometric combustion conditions to take advantage of lean combustion as much as possible across the load range.
  - The project will determine optimal engine combustion strategies and enabling components to maximize engine efficiency and fuel consumption improvements.

- Evaluation against Project Barriers:
  - **Goal:** Combined increased lean operation >1.5 λ & EGR >20% show increased efficiency.
  - **Key Enablers:** Ignition systems tested to date has allowed extending the boundary limit of acceptable combustion operation. ATS simulation under development.
  - **Targets:** <37% peak BTE baseline extended to ~39% to date. Ultra lox NOx capable; Known HC solutions to be implemented.

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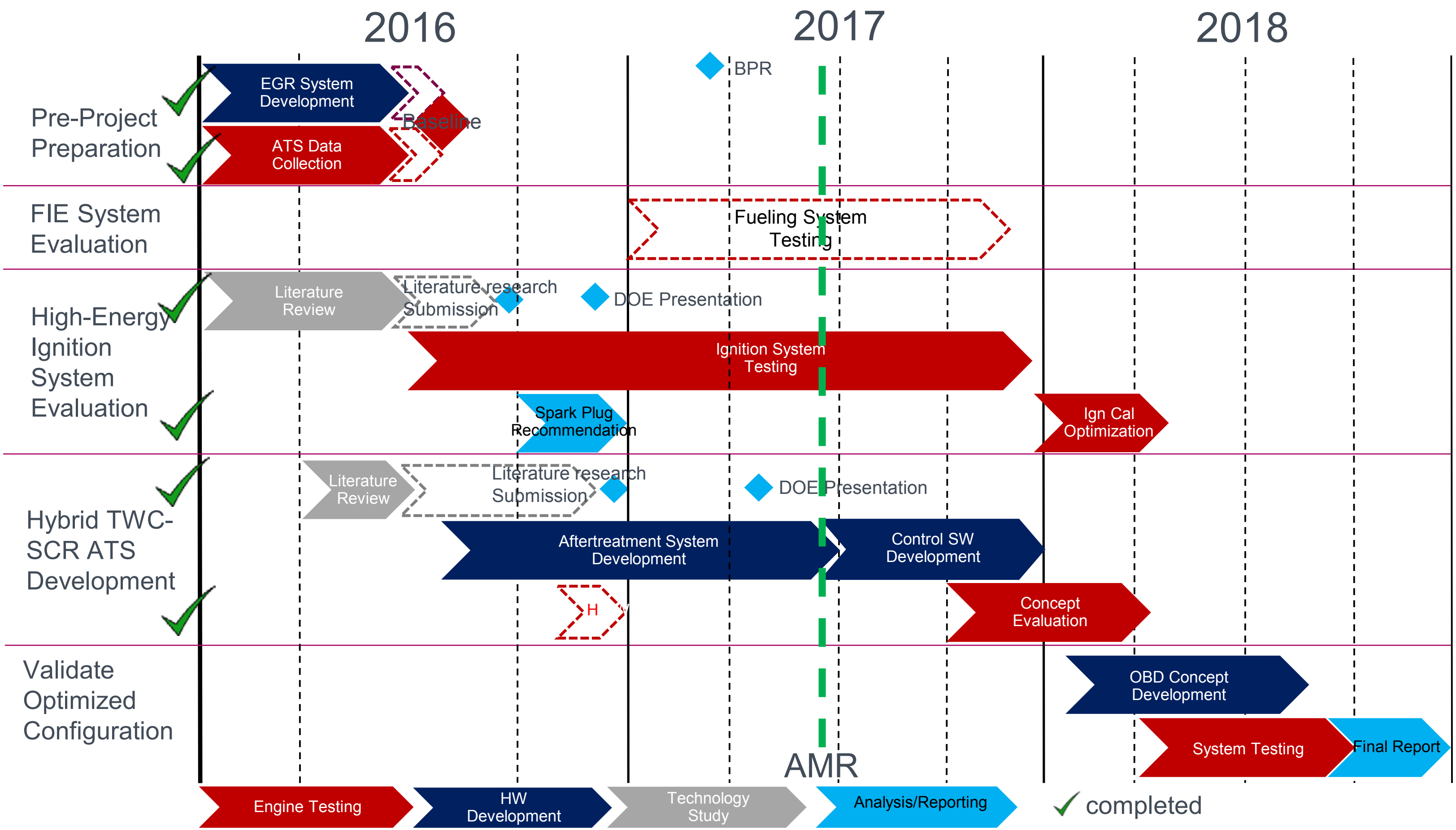
Approach/Milestone



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Technical Accomplishments and Progress

- Baseline:

	HC [g/bhph] (CP)	CO [g/bhph] (CP)	NOX [g/bhph] (CP)	CO2 [g/bhph] (GHG)	BSFC [g/bhph] (Efficiency)	BSFC [g/kWh] (Efficiency)
WP10NG Stoich w/EGR baseline (TP)	0.70 THC	6.7	0.016	500	165	221
US 2017 HHDD Standard (TP)	0.14 NMHC	14.4	0.200	460	———	———
WP10NG Lean w/o EGR, no ATS (EO)	5.0 THC	3.4	13.2	440	151	202

Baseline already able to achieve ultra low NOx levels, meets CO standard, with work to be performed in HC & CO2 areas.

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Technical Accomplishments and Progress

- Passive SCR Concept:

Ammonia generation mode

Engine → TWC → SCR →

Engine	TWC	SCR
Stoich/rich (0.96) ~38% BTE	**NOX conversion** NH3 generation (low NOx production)	NH3 Storage

Change between operating modes as needed to maintain NOX conversion

Low tailpipe NOX always!

High efficiency mode

Engine → TWC → SCR →

Engine	TWC	SCR
Lean w/EGR (1.3) ~42% BTE	“Inactive” for Nitrogen compounds, Possible oxidation of HC and CO	**NOX conversion** NH3 Consumption

Toggling between rich & lean operation provides both high efficiency & cost effective emissions control:
Lean provides high efficiency but high NOx, while rich operation generates natural ammonia to breakdown NOx.

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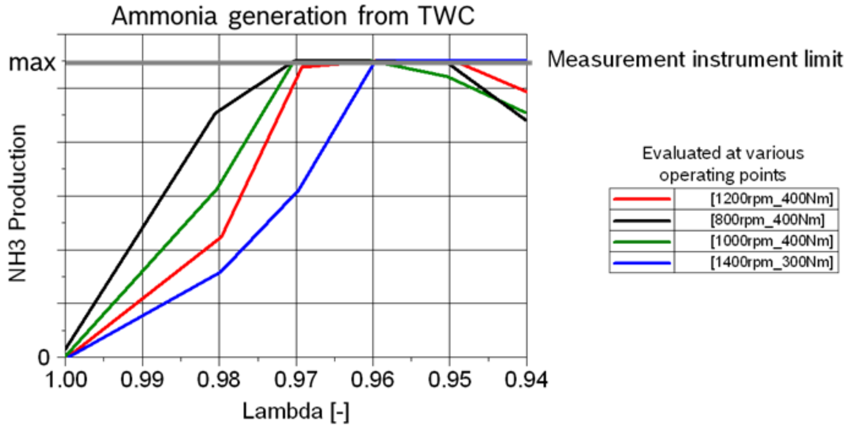
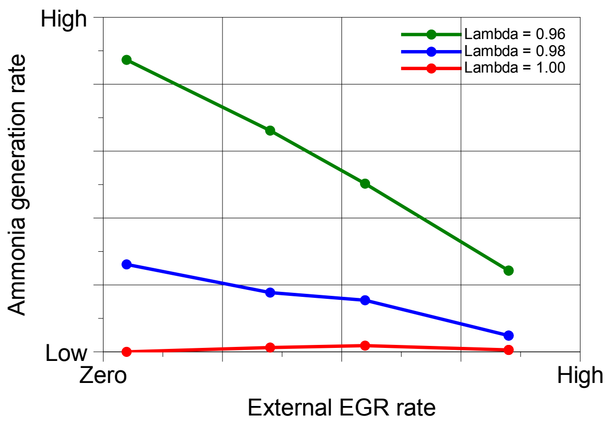
Technical Accomplishments and Progress

- Ammonia Generation via Lambda level & EGR rate:





High levels of ammonia able to be generated, at minimum levels of richness;
Ammonia generation linear to EGR rate, across lambda levels

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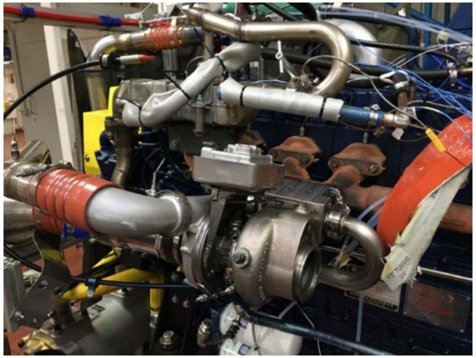
Technical Accomplishments and Progress

- Engine configuration evolution:

As rec'd Lean w/o EGR
(end-mount OE baseline turbo)

Gen 1 Stoich & single path EGR
(center-mount baseline turbo)



Gen 2 Stoich & dual path EGR
(resized turbo)

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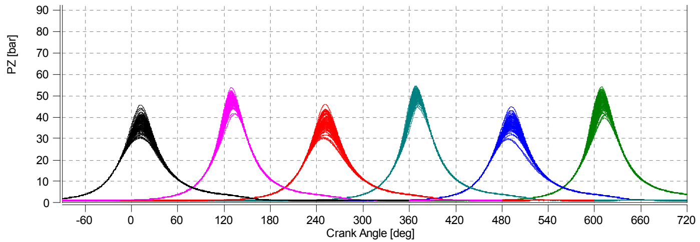
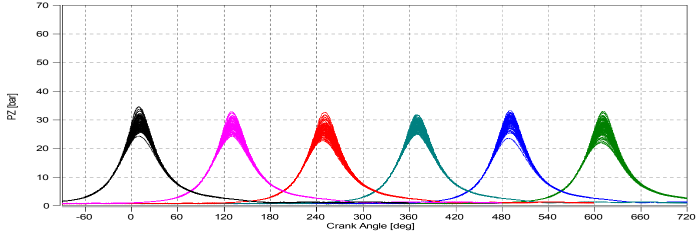
Technical Accomplishments and Progress

Combustion Stability

- Refinement of 1st gen turbo & EGR system into a revised system, based on initial results:



Initial Turbocharger Size and EGR System



Revised Turbocharger Size and EGR System

Single scroll fed EGR caused cylinder pressure imbalance; Dual scroll fed EGR equalized pressure balance.

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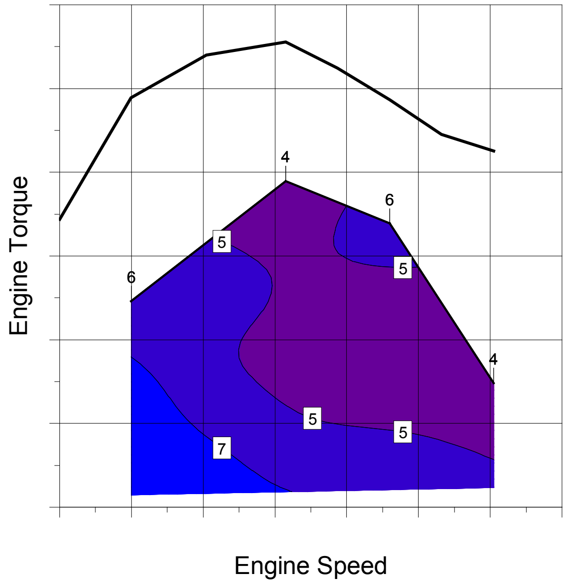
Technical Accomplishments and Progress

- High Dilution Efficiency Benefit (full lean + EGR) over Stoich.



- Subset of overall speed-load map where lean and EGR operation is stable with 65mJ ignition coils
- Dilute homogeneous combustion improves BSFC compared to stoichiometric (on average 1.5 lambda and 9-11% EGR at points represented here)

Percentage of BSFC improvement in Lean + EGR over baseline Stoich + EGR identified.

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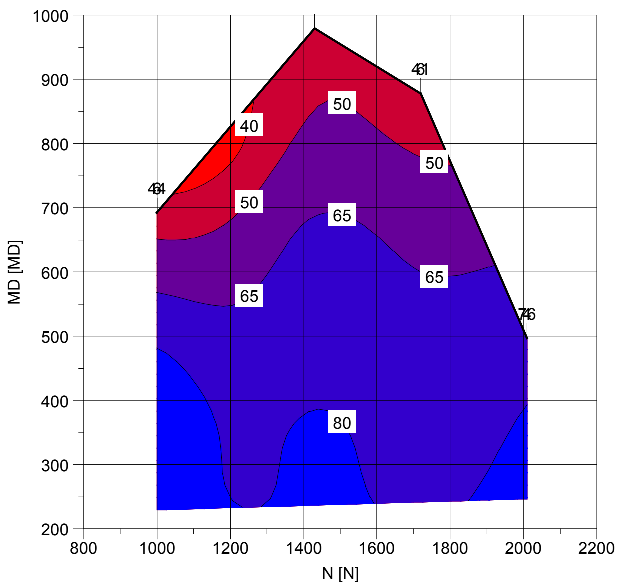
Technical Accomplishments and Progress

Exploration of passive SCR operation:

Combined operation switching between ammonia generation and lean +EGR

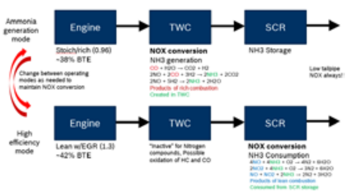
Percent of operation in lean+EGR mode



Speed [rpm]	Torque [Nm]	Lean BSFC [g/kWh]	Lean mode improvement over stoich [%]	Percentage operation in Lean mode [%]	Combined operation improvement over stoich [%]
1000	230	255	7.7	94	7.0
1000	460	207	7.9	83	5.7
1000	697	196	7.2	53	2.1
1210	264	245	7.9	79	5.3
1210	526	206	5.5	67	1.8
1210	787	194	6.2	63	2.8
1430	327	236	6.1	82	3.7
1430	656	202	4.8	69	1.2
1430	976	196	3.9	56	0.8
1720	292	252	6.3	76	3.2
1720	583	212	3.2	66	0.0
1720	878	198	5.8	41	-0.4
2010	247	279	5.4	84	3.6
2010	497	224	4.0	76	1.1

- Operation time in lean+EGR mode calculated based on NH3 generation in rich mode vs NOX in lean+EGR mode
- Assume complete storage of NH3 in SCR

Passive SCR components, reactions and control concept



Percentage of operation time in lean (efficiency) mode vs. rich (ammonia generation) mode approximated.

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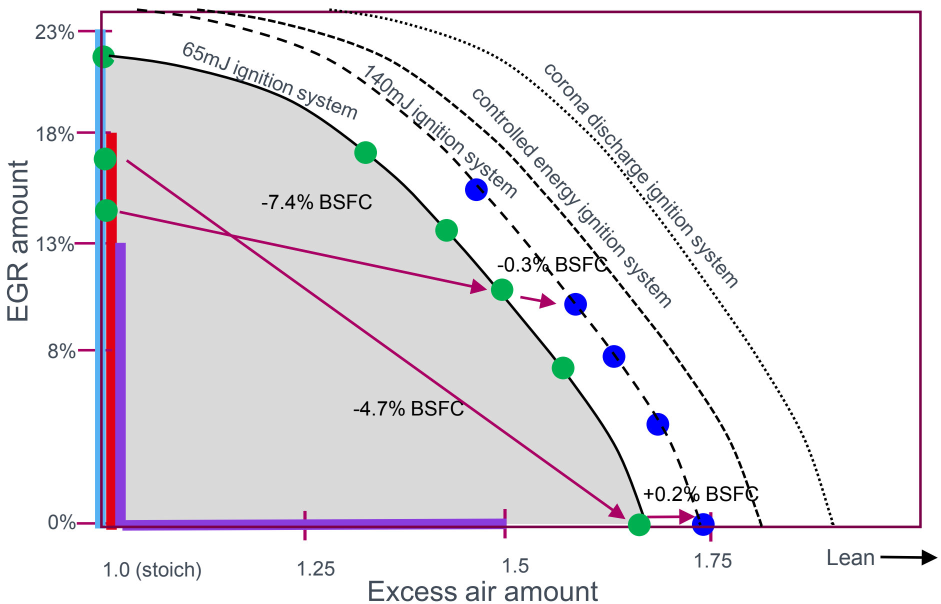
Technical Accomplishments and Progress

Illustration of high dilution combustion concept with influence of ignition system capability



	Engine mapping completion	
65mJ Stoich	●	Measured with Power Mini coil
65mJ Lean+EGR	●	Measured with Power Mini coil
140mJ Lean+EGR	◔	Measured with Power Plus coil
Bosch CEI Lean+EGR	○	Predicted increased dilution
B-W Corona Lean+EGR	○	Predicted increased dilution

Increased energy with conventional ignition increased dilution limit for combustion. Further efficiency improvement observed at some operating points. Optimization of air system controls for best efficiency necessary with high dilution combustion concept.

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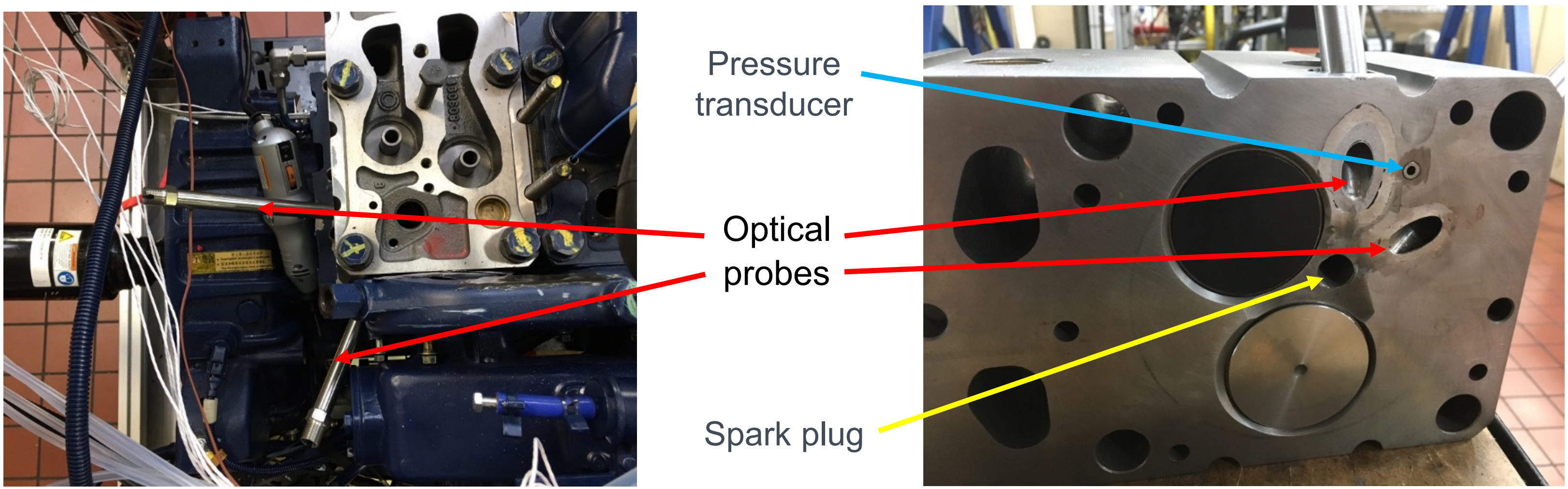
Technical Accomplishments and Progress

Optical instrumentation for ignition system comparison

- Borescope sleeves installed into cylinder head.

External View

Combustion Chamber View



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Responses to Reviewers' Comments

- Project was started in January 2016 and therefore not reviewed in last year's AMR.

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Collaboration with Other Institutions

Organization	Role	Responsibilities
Robert Bosch LLC	Project Lead	Technical project management, Engine calibration, Determine optimal control levels for maximum efficiency while achieving emissions goals.
University of Michigan	Partner	Evaluation of ignition systems. Literature review of advanced ignition systems. Design and implementation of high-speed, infrared imaging system. Execution and analysis of optical measurements to quantify effects of ignition systems.
PNNL	Partner	Aftertreatment concept selection. TWC-SCR ATS literature review to assist in developing simulation model development. Evaluation of catalyst samples on Synthetic Gas Bench in support of model refinement. Develop kinetic model & kinetics simulation in support of determining optimum engine operational controls for passive SCR operations to achieve goals.
BorgWarner	Vendor	Supplier of corona discharge ignition system, design, development & application support to apply to the project test engine.
Weichai America Corp.	Support	Base engine information support, including CAD models and wiring diagrams.

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Remaining Challenges and Future Research

Key Challenges

- Achieving target efficiency levels
- Develop “toggling” operation for high efficiency & low emissions
- Achieving low emissions
- Develop cost optimized model

Any future work is subject to change based on funding levels.

Future Research

BP2 (April – December 2017)

- Determine boundary limit for remaining ignition systems:
  - Completion for 140mJ coil
  - Bosch CEI system
  - Corona Discharge
- Assess flame propagation for all systems via optical measurements
- Complete simulation model for aftertreatment system, & identify optimal solution
- Assess efficiency benefits expected via simulation model of various drive cycles

BP3 (January – September 2018)

- Develop & verify final systems via transient cycles
- Submission of final project report

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Summary

- Testing activities to-date indicate that efficiency improvement in high dilution environment (Lean + EGR) can be realized.
- Further testing per plan to be performed to determine if advanced ignition systems can push the high dilution boundary further, with corresponding improvements in efficiency, or not.
- Benefits of passive SCR & system cost optimization to be determined in upcoming periods.

Features	% Improvement
Baseline Engine BSFC	<37% peak
Developments to-date BSFC	~39% peak
Project Target BSFC	42%
NOx emissions to-date	0.016 g/bhp-h
Low NOx standard (target)	0.200 g/bhp-h
Ultra Low NOx standard	0.020 g/bhp-h

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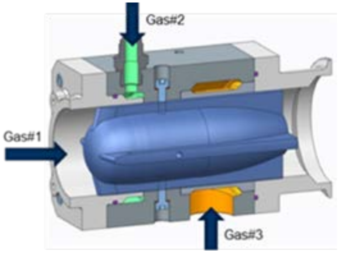

THANK YOU! QUESTIONS?

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